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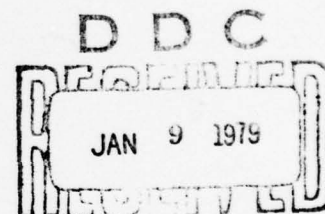NATIONAL BUREAU OF STANDARDS-1963-A

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Multiple Conceptual Models of a Complex System

Albert L. Stevens and Allan Collins

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Cambridge, Mass.

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This paper describes some of the strategies and knowledge tutors use in teaching about the causes of rainfall. Underlying a tutor's ability to diagnose and correct students' misconceptions are a set of <u>models</u> of the rainfall process. These models allow students to understand a system from different points of view and to derive the consequences of changing different critical variables in the model.

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Students' misconceptions often derive from incorrect models of the system and diagnosing these misconceptions requires expert knowledge of what distortions can occur in student's models.

Abstract

This paper describes some of the strategies and knowledge
tutors use in teaching about the causes of rainfall. Underlying
a tutor's ability to diagnose and correct students' misconceptions
are a set of _models_ of the rainfall process. These models allow
students to understand a system from different points of view and
to derive the consequences of changing different critical variables
in the model.

Students' misconceptions often derive from incorrect models
of the system and diagnosing these misconceptions requires expert
knowledge of what distortions can occur in student's models.

INTRODUCTION

Designers of intelligent computer aided instructional systems have spent much effort developing techniques for representing knowledge, interpreting student inputs, presenting clever displays, and providing ways to motivate students to interact with the systems. These efforts all reflect important aspects of the problem of providing an environment which facilitates learning. Nevertheless, we believe that most efforts to date have neglected one of the most important aspects of the problem: a deep and thorough analysis of the strategies and knowledge that a skilled teacher uses to effectively communicate a subject matter.

Our efforts have been directed at analyzing the strategies and skills necessary to teach complex topics such as geography, climate, and meteorology. We have found that the skills necessary are indeed complex. A teaching dialogue, rather than following some a priori knowledge structure is best characterized as a mixture of diagnosis and correction strategies where the tutor probes the student's understanding and uses the surface errors as clues about the deeper misconceptions that they manifest. These diagnosis and correction strategies require knowledge about common errors and their relationship to misconceptions, an understanding of the types of real-world experiential knowledge that students bring to bear on understanding new problems, and an understanding of the ways that this real-world knowledge can be applied.

In this paper, we present some of our current analyses and ideas about the teaching process. We briefly review our analyses of

the teaching strategies we have observed in dialogues and the goal structure necessary to support them. We present some of the errors that we have observed students make about the causes of rainfall and show how these can be characterized as arising from deeper misconceptions. In the final section, we describe our ideas about some of the conceptual models we believe are necessary to deal with students learning about rainfall and suggest how they interact to produce understanding.

Teaching Strategies

One of our first goals was to characterize the set of strategies that teachers use in dealing with students' questions and responses. We examined tutorial dialogues that used a Socratic or case method. Based on analyses of dialogues covering several different topic areas, we were able to derive a set of pattern-action rules that account for many of the specific teaching strategies used by the tutors (Collins, 1977). The rules assume a simple knowledge structure which represents the functional dependencies of the domain being taught. For the purposes of the analysis, we assumed that functional knowledge was represented as an and/or graph. The and/or formalism serves basically to differentiate between necessary and sufficient conditions for the various factors taught. For example, rice growing requires three necessary factors: a flooded flat area, fertile soil, and warm temperatures. A flat area is the result of either of two sufficient factors: flat terrain or terracing.

- 2 -

The teaching rules were formulated in terms of a conditional test, paired with an action to perform if the test is true. We can illustrate this analysis with two example rules:

(1) If the student gives as an explanation a factor that
        is not an immediate cause in the causal chain,
     then ask for the intermediate steps.

(2) If the student gives as an explanation one or more
        factors that are not necessary,
     then formulate a general rule by asserting that the
        factor is necessary and ask the student if the
        rule is true.

The analysis in Collins (1977) consists of twenty-four rules. This set captures much of the local structure of teaching dialogues but fails to deal with global structure. As was pointed out in that paper, characterizing the structure of the global interactions requires additional layers of theory.

Goal Structure

In order to characterize the global structure of teaching dialogues, we have conducted additional dialogues. In these, we attempted to open another channel into the tutor's thinking by isolating the tutor from the student, having them communicate over linked terminals, and taking a verbal protocol from the tutor. In the protocol we asked the tutor to comment on two aspects of the process: (1) what he thought the student knew, or didn't know, based on the student's response, and (2) why he responded to the student in the way he did. This technique provides insights into how the tutor organizes the knowledge taught, how the tutor develops a model

of the student, and how these two factors influence the tutor's choice of questions and responses to the student.

We developed the outlines of a theory of tutors' goal structures. The goal structure we derived is summarized in Table 1. The top level goals are: (1) refine the student's causal model and (2) refine the student's procedures for applying the model. These directly govern the selection of cases. As the student's knowledge becomes more refined, moving from an understanding of first-order factors to higher-order factors, cases are selected which are exemplary of the factors the tutor is trying to teach. As the student's predictive ability becomes refined, cases are selected which are progressively more novel and complex, taxing the student's predictive ability more and more.

The process of achieving these top-level goals involves two types of subgoals: diagnosis and correction. Both of these subgoals govern the selection of basic strategies.

The purpose of diagnosis is to discover gaps and misconceptions in the student's knowledge. This generally requires that the tutor probe the student by asking for relevant factors, by requiring the student to make predictions about carefully selected cases, and by trying to entrap the student into making incorrect predictions. It is clear from our analysis of human dialogues that diagnosis cannot be completely characterized in terms of a simple mapping between surface errors and underlying misconceptions. Rather the process involves sophisticated use of a student model and knowledge about common misconceptions in order to simulate the student's reasoning

- 4 -

Table 1

Outline of a Socratic Tutor's Goal Structure. The manifestations refer to
the rules described in Collins (1976) and Stevens and Collins (1977).

<u>Goals</u>	<u>Manifestation</u>
Refine the student's causal model moving from 1st to nth order factors.	Case selection rules: Select cases that are exemplary of the relevent factor.
Refine the student's procedures for applying the causal model to novel cases.	Case selection rules: Select less familiar cases, exemplary of new factors.

<u>Subgoals</u>	
Diagnose the student's "bugs", (i.e. the difference between the student's knowledge and the tutor's knowledge.)	Ask-for-factor rules. Prediction rules. Entrapment rules. Probe-reasoning-strategy rules
Correct the diagnosed bugs	Inform-student rules Missing-factor rules Forming hypotheses rules Testing hypotheses rules Information-collection rules

- 5 -

processes and pinpoint the underlying misconceptions or missing information. In some situations, a single answer may reveal a whole set of misconceptions, while in other cases, the tutor must carefully probe the student, testing alternative hypotheses.

Typically, when a misconception is diagnosed, the tutor attempts to correct it. This may require a single statement for simple factual errors or an extended dialogue to correct problems in the student's causal model. In Stevens and Collins (1977) we illustrate the application of this goal structure model by using it to analyze a tutorial dialogue.

Our outline of goal structure is relatively general and probably can be applied to many different knowledge domains and tutorial interactions. However, in order to specify it in detail, we need to know what the misconceptions are, how they can be represented, how they are diagnosed from errors and how they can be corrected.

Conceptual Bugs

In a sense, the previous two sections describe preliminaries to some of the hardest problems that must be faced. What are the conceptual bugs? What knowledge and knowledge representation is necessary to support the basic teaching strategies and the global goal structure? What knowledge and knowledge representation is necessary to correct diagnosed bugs?

We have recently completed an experiment to examine the misconceptions that occur in understanding rainfall (Stevens,

Collins & Goldin, in press). We compiled a systematic set of questions by generating an and/or graph representation for the causes of heavy rainfall. For each node in the graph we generated a question that asked what the prior factors were and a question that asked what the subsequent factors were. This resulted in 32 questions which we assembled into a test booklet and presented to eight students. Some example questions are: "How is the moisture content of the air related to heavy rainfall?", "What role does rising air play in causing rainfall?" and "What causes evaporation?". At the top of the test, we included a paragraph that described what we meant by heavy rainfall and instructed the students to answer all questions in the context of that paragraph. We asked the students to answer all questions even if they felt they were just guessing because in previous work, we have found that students often know a good deal more than they think they do.

To analyze this experiment, we first tabulated all responses that we judged to be errors. We subsequently analyzed these errors by classifying them according to a basic set of bugs. Development of the set of bug types occured in combination with the error analysis. Our analysis revealed two points of interest: (1) A particular conceptual bug is often shared by several students, and (2) a particular conceptual bug is often manifested in different ways. For example, one of the most frequent bugs is the "Cooling-by-contact" bug that occurs for 6 of the 8 students. Some verbatim examples of manifestations of this bug are:

(1) "Cold air masses cool warm air masses when they collide."

(2) "Winds cause air to cool."

(3) "Mountains cause condensation because cold land touching warm air causes condensation."

(4) "Cold fronts, wind, snow and rain cause air to cool."

(5) "Cold air masses cool the clouds so the rain falls."

None of the above types of cooling are of any consequence in causing heavy rainfall. The type of cooling necessary occurs when an air mass is forced to rise. The rising results in expansion and energy loss.

We identified sixteen different conceptual bug types from this analysis. Table 2 shows these sixteen bugs in order of frequency. Using these sixteen misconceptions we were able to account for 58% of the errors. Many of the remaining errors are factual errors, for example "Heavy rainfall occurs only in warm areas", or naming errors, for example "When water evaporates, it turns to steam". (Heavy rainfall occurs in many cool and cold areas; the standard term in meteorology for the product of evaporation is water vapor.)

Note that the mapping between the manifestations and the bugs is often not simple. There are sometimes obvious surface clues; for example, the sun as an agent of "warming air" indicates the Heating-by-radiation bug. Other cases require a more subtle analysis; for example, detecting the Small-moisture-source bug requires knowledge about relative sizes of bodies of water.

- 8 -

Table 2. The set of observed misconceptions.

Misconception	Number of Subjects	Example
(1) Cooling-by-contact	6	"Mountains cause condensation because cold land touching air causes condensation."
(2) Heating-by-radiation	6	"The sun warms the air."
(3) Small-moisture-source	5	"A 12 by 12 by 10 foot pond is enough to cause rainfall."
(4) Rising-causes-increased-pressure	3	"Rising air makes the moist air rise, pressure increases ..."
(5) Absorbtion-by-expansion	3	"...decrease in pressure causes water molecules to expand, causes evaporation."
(6) Heating-by-contact	3	"...land warms the air at night."
(7) Squeezing-causes-condensation	2	"Putting pressure on air masses causes condensation."
(8) Temperature-of-water-irrelevant-for-evaporation	2	"Temperature of water is unrelated to evaporation."
(9) Temperature-differential-causes-evaporation	2	"Air has to be cooler than the body of water for evaporation to occur."
(10) Insufficient-warming-of-wat r	2	"A current can be warm because it comes from a warm source of water--for example, a lake which is warm."
(11) Heating-causes-condensation	1	"Air warming up causes rainfall."
(12) Winds-cause-pressure-increases	1	"Winds are forceful and cause various air pressures."
(13) Cooling-causes-evaporation	1	"When a body of water is cold, it evaporates."
(14) Rising-results-in pressure-equalization	1	"Air that is warmer is expanded and has less pressure. It rises until its pressure is equal to surrounding air."
(15) Cooling-cause-air to-rise	1	"Cooling causes air to rise."
(16) Evaporation-causes-air-to-rise	1	"Evaporation causes air to rise."

MODELS

We believe that the bugs we have isolated are still rather shallow, reflecting even deeper levels of misconceptions in students' knowledge. The major reason for this is that the bugs themselves seem to form patterns and the patterns seem best explained as the result of deeper problems in the students' knowledge. In this section, we discuss some of the issues that we see as important in understanding where bugs really come from and what is necessary to adequately characterize the knowledge a student must acquire to understand a complex system.

The view we propose is that people maintain multiple, procedural representations, which we call models (Collins, Brown, & Larkin, 1979; Stevens & Collins, 1977). We often refer to these models as simulations (Brown & Burton, 1975), but the models are not complete simulations of the world. Simulation models only make it possible to represent certain properties of the world. The properties represented may be both incomplete and incorrect, but by knowing how they interact, it is possible to "run" the model under different conditions to examine the consequences. Thus, a simulation model is like a motion picture that preserves selected properties of the world.

There are three themes that run through our discussion of models. These themes have strong implications for the design of expert CAI systems.

The first theme is that any model can be more or less sophisticated, and learning is largely a process of refining models so that they correspond better with the real world. In this paper we will give examples of several kinds of refinement that we have observed:

1. Adding parts to a model: A model might be refined by adding different parts to it. For example, if molecules of water are represented as billiard balls bouncing around in a container, the surface tension of the water might be added to the model by representing it as a partially reflecting mirror.

2. Replacing parts of a model: A model might be refined by replacing one part of the model with another part. For example, the partial-mirror model of surface tension might be replaced by a view that surface tension results from the unbalanced forces of molecular attraction at the surface of water.

3. Deleting parts of a model: A model might be refined by removing irrelevant parts. For example a functional model of evaporation that includes the temperature of the heat source could be refined by deleting this aspect of the model.

4. Generalizing parts of the model. A model might be refined by generalizing from particular cases. For example, a model of how the Gulf Stream affects rainfall in Europe might be generalized to how currents flow around a rotating sphere and affect land masses on the sphere.

5. <u>Differentiating parts of the model</u>. A model might be refined
by breaking down parts of the model into subcomponents. For
example, a simple functional model (see Fig. 1) might be
further differentiated to specify component subprocesses.

The   second   theme   is   that   models   provide the power to
consider alternative possibilities and to derive   predictions   about
novel situations. It is possible to look at alternative situations
by running the model with different values assigned to   its
variables.   To   make   predictions   it   is often necessary to choose
critical values for particular variables in order to determine   what
are   the   most   likely outcomes and what are the boundary conditions
for which the model holds. Thus, the power of models derives from
the ability to run them under different assumptions.

The   third   theme   is   that   students'   underlying
misconceptions derive from simplifications or distortions in   their
models.   We will show how some of the rainfall misconceptions
described earlier come out of incorrect underlying models. We think
it is possible to counteract some misconceptions by checking results
found in one model against another model.   Learning how to use
different models and to map between them may in fact be one of the
most important aspects of understanding complex systems.

Models of the Weather System

We can illustrate these notions with four models that we
have observed people use in understanding meteorological processes.
Two of these models are concerned specifically with evaporation

- 12 -

processes. The first of these we call a simulation model of evaporation and the second a functional model of evaporation. The other two models include evaporation processes as local aspects of more global processes. The third model we call a water-cycle model and the fourth model a climate model. We will illustrate rudimentary forms of these models which we have observed people use and have seen in text books. We will also give more sophisticated versions of each model, though of course the sophisticated versions are not completely correct either.

The notion of simulation of the weather can best be understood in terms of a simulation game, such as the Civil War game marketed by Avalon Hill. In the Civil War game one player represents the North and the other player represents the South. It is a game of attack and strategy much like Risk, Diplomacy, or even chess. The game consists of a board, playing pieces and a seventeen page booklet of rules. The board and pieces represent the state of a simulated war at a particular moment in time. The rules embody many of the constraints which existed physically and politically at the time of the American Civil War. For example, the rules allow supplies to be moved rapidly along rivers and railroads. Thus it is clear why Vicksberg figured in an important battle; it is located where a major railroad line crosses the Mississippi River. Furthermore, it is clear why the North attacked along the East coast and the Mississippi rather than through the Appalachian mountains. The rules allow troops and supplies to move through the the Appalachians at only one tenth the rate allowed through other parts of the region.

Given such a simulation game, it is possible to consider how likely it was that the North would win the Civil War. The answer is given in terms of the frequency that the North wins any game played under the set of rules. To evaluate such a frequency, it is necessary to consider a set of critical cases. These critical cases must be constructed by examining what happens when the North and South apply different general strategies: for example when the North centers its strategies around a naval attack, a Western campaign, an Appalachian campaign, or an East coast campaign. In fact, it turns out that the North usually wins.

It is also possible to understand how people process hypothetical questions. For example, we can consider what would have happened if the North had invaded the South through the Appalachians instead of along the East Coast and down the Mississippi. The answer comes from characterizing the set of games that are played when the North invades through the Appalachians. For example, a characterization of those games might be that the South's chances improve dramatically and that the winner depends on certain tactical decisions made in any battles that take place in the Appalachians. In fact, since movement is so difficult through the mountains, the South has ample time to anticipate and counter any move by the North so the South usually wins those games.

These examples illustrate some of the potential power inherent in the simulation approach. Simulations do not represent every aspect of the world (in the Civil War game, there is no provision for the assassination of Jefferson Davis, or the invention

of the airplane) and a large amount of information is necessary to accomplish the simulation, but simulation models do enable one to test out the potential consequences of varying certain aspects of the real world.

A Simulation Model of Evaporation

One possible model of the evaporation process views air molecules as billiard balls. In the rudimentary version of this model the water particles are thought of as billiard balls bouncing around, hitting each other, and sometimes flying out of the water into the air. One aspect of this model that one might notice is that particles flying out of the water come from the area of the water nearest the surface. The effect of temperature in this model is to speed up the rate at which the billiard balls move. As the particles bounce around, sometimes those near the surface fly off. As the particles are sped up by increasing their temperatures, the whole process speeds up and so more fly out of the container in a given period of time. Thus, with these few simple local properties, a person can run the model and derive certain consequences, for example, that water evaporates from the area near the surface and that warmer temperatures result in faster evaporation.

Note that even for this rudimentary model, the description is only a very rough approximation to an actual model. It does not explicate the set of laws, processes and control structures that enable the model to be run under different conditions. For example, the laws governing movement and collision of particles must be

internalized in the model so that when run, the proper consequences
of differences like particle speed can be derived.

A more sophisticated version of the model may incorporate
the notion of molecular attraction. Molecular attraction can be
seen as a force which pulls the billiard balls closer together.
Thus, there is a constant pull between the motion of the billiard
balls trying to move them apart and the attractive forces trying to
bring them together. When the motion is small, the attractive
forces can hold the billiard balls together. This corresponds to
the liquid state of water. As the motions increase, they overcome
the forces of molecular attraction and the billiard balls fly apart.
This corresponds to the vapor state of water. Note that because the
amount of motion is an average across all molecules, some will be
moving faster than others. So at any time, some molecules will be
moving rapidly enough to break free of their neighbors. However,
because these molecules are surrounded by millions of other
molecules bouncing around rather slowly, subsequent collisions will
slow them down and they will be captured again. It is only those
near the surface that really have a chance to break free from the
others, pass into the less-densely packed air molecules and remain
non-liquid.

The concepts in this model can be used to infer and
understand additional properties of water. For example, molecular
attraction explains surface tension as the result of the unbalanced
forces of attraction that occur near the boundary between the water
and air. At the boundary, there is a net pull inward, compressing
the molecules closer together.

We can illustrate some of the power of this more sophisticated model by showing how it can be used to deal with three different changes to the basic situation of a standing body of water. The model may not be correct, but at least it allows one to make certain predictions.

The first change is to add a layer of oil to the surface of the water (as the world seems to be doing to its oceans). In the model the effect of oil is to increase the thickness of the surface barrier, and thus to increase the length of the path for particles passing from the water into the air. Thus, the prediction from the model is that a layer of oil on the water should decrease the evaporation rate.

The second change is to make the water choppy instead of smooth. Choppiness increases the surface area of the body of water and thus increases the surface area for particles to escape through. So choppiness should increase the evaporation rate.

The last change is to add winds. We can add winds onto the model in at least two different ways. Since winds increase the choppiness of water, they increase the evaporation rate. They also act to bring new portions of the air mass in contact with the surface of the water. If the air near the surface contains a large number of water molecules, then because they are moving randomly around, a large number will return to the water. If there is a large enough number, there will be as many returning as are leaving and there will be no net evaporation. Thus, winds blow away the part that is saturated and bring in new parts of the air mass where

- 17 -

there is a smaller density of water molecules. Winds thereby increase the amount of evaporation.

These examples illustrate some of the power of such a model. There is a large amount of knowledge that people must have to construct the model; for example, that temperature is represented as average amount of molecular movement, that average movement is related to individual movements in certain ways, that winds affect both choppiness and mixing of the air mass, and that forces can balance or add together. Any such knowledge that is missing or forgotten is likely to lead to the wrong conclusions. But despite these limitations, such a model gives a person enormous power for making new predictions.

A Functional Model of Evaporation

A rather different perspective on the evaporation process is seen in the functional representation developed by Stevens et al (in press) to account for people's misconceptions, and in the finite-state-automaton model of Brown, Burton, and Zdybel (1972). This functional perspective describes the input variables and output variables in the functional relationships involved in evaporation.

The upper part of Figure 1 shows a rudimentary form of such a functional model. It is what a person might derive from watching water heating on a stove or evaporating from a dish in the sun. In this rudimentary form of the model, the amount of evaporation is a function of the amount of heat affecting the water. Thus, if the burner on the stove is turned on high or the sun's rays
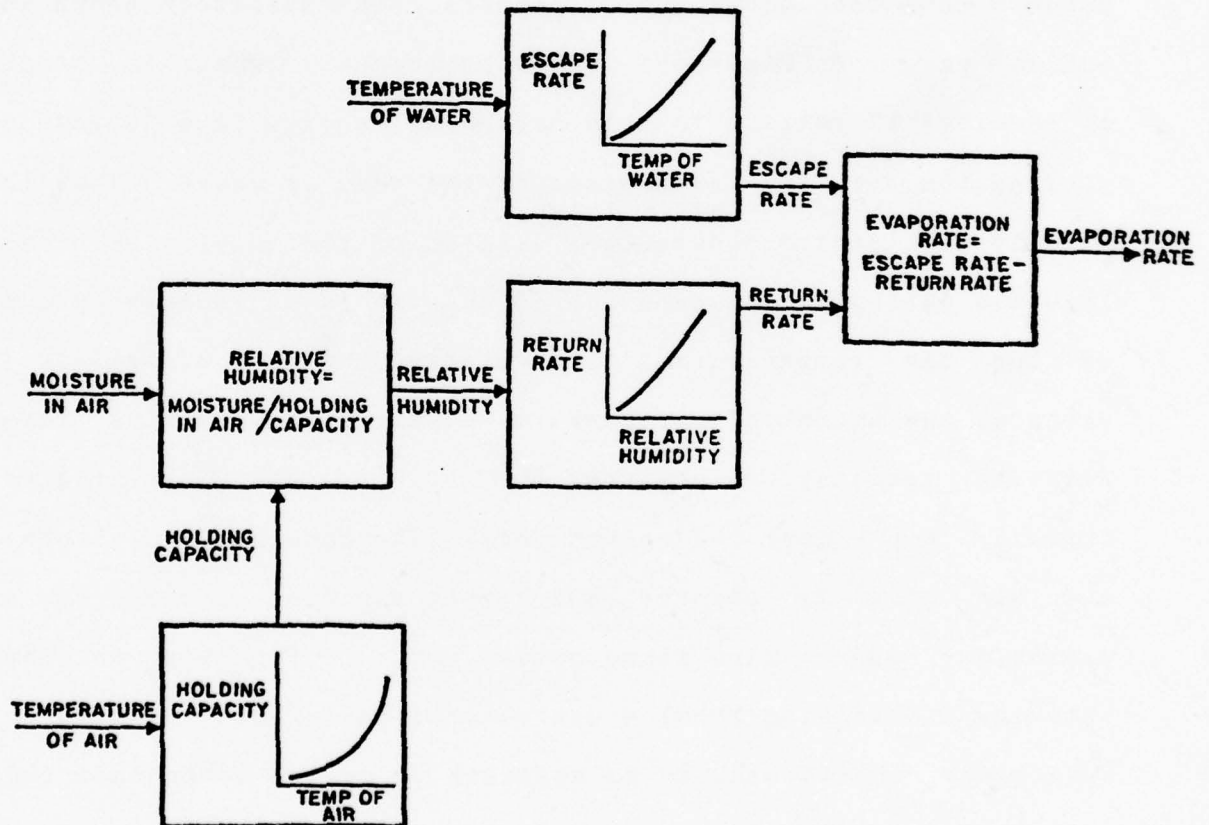
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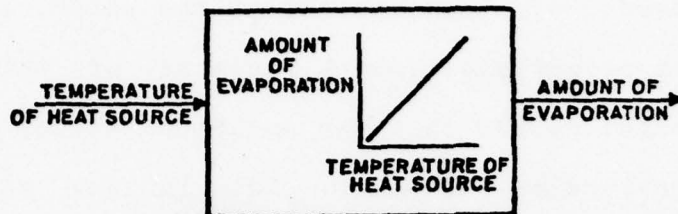
MORE SOPHISTICATED VERSION

Figure 1. Two versions of a functional finite-state-automaton model of evaporation.

- 19 -

are particularly hot, more water will evaporate from the container. The person probably would not know the exact functional relationship; just that the rate of evaporation is an increasing function of the amount of heat applied to the water. Different people might construct slightly different versions of this model; for example, they might decide that the amount of evaporation is a function of the temperature of the water. But in any case, they must construct something like this model.

A more sophisticated version of the model might break the process down into different components. The breakdown shown in the bottom part of Figure 1 is approximately what is taught in meteorological texts. In this breakdown, escape rate is seen to be a function of the temperature of the body of water. This is more precise than in the rudimentary version of the model. At the same time the water-holding capacity of the air is an increasing function of the air temperature. The relative humidity of the air is the ratio of the amount of moisture in the air to its holding capacity. Relative humidity determines the return rate: the higher the humidity, the higher the return rate. The amount of moisture that the air actually absorbs is a simple function of these two output variables: escape rate minus return rate. For the purposes of thinking and talking about evaporation a person can treat these five functional relationships as separate or he can merge them together with the temperature of the water, the temperature of the air, and relative humidity as input variables and the amount of moisture the air absorbs as the output variable.

The differences between the rudimentary version of the model and the more sophisticated version gives some idea of how people can refine this kind of model of a process. In particular, they can learn the controlling variables on different processes; they can learn better the functional dependencies between the input variables and the output variables; they can learn to break the process into its various component subprocesses. Both the texts and the teaching dialogues we have looked at have emphasized these aspects of evaporation. We think this is because the functional viewpoint is critical both for making predictions about the evaporation process and for talking about it.

The mathematical equations for evaporation come from quantizing the functional relationships between the input and output variables of the model, defining the boundary conditions, defining the critical changes of state, and coupling these all together. Brown, Burton and Zdybel (1972) have shown how the cross product of local finite-state automata can be run until equilibrium is reached to determine the effect of any change in an input variable. Stevens et al (in press) have indicated how large a proportion of teaching dialogues concern the various input variables, output variables, and functional relationships. They further show how many student misconceptions can be represented as perturbations of various parts of such a model.

We should point out that and/or graphs can be derived by instantiating the variables of such a model. For example, the model in the lower half of Figure 1 can be instantiated to represent a

case of high evaporation as shown in Figure 2. In teaching about functional relationships, teachers often talk about input and output variables in these instantiated forms (Collins, 1977).

The simulation models and the functional models give different perspectives on the evaporation process, but it is important to be able to map between the two kinds of models. Undoubtedly people often have inconsistencies between different models; for example the rudimentary versions of the two models are inconsistent in that the rate of evaporation is related to the temperature of the water in the simulation model, but to the temperature of the heat source in the functional model. Refinement of models is in part a process of making different models consistent and working out the mappings between them. Thus the more sophisticated versions of each of these models attempt to preserve consistent mappings between them. For example, evaporation rate is treated functionally as an equilibrium process in the functional model, which enables it to map with the process of water molecules entering and leaving the body of water in the simulation model. We suspect that it is important to have models which provide such different perspectives on understanding a process. The simulation model provides an understanding of the mechanism or rationale for the interacting variables described by the functional model. The functional model provides a summary of the physical processes and an indication of the critical boundary conditions for which it is valid.
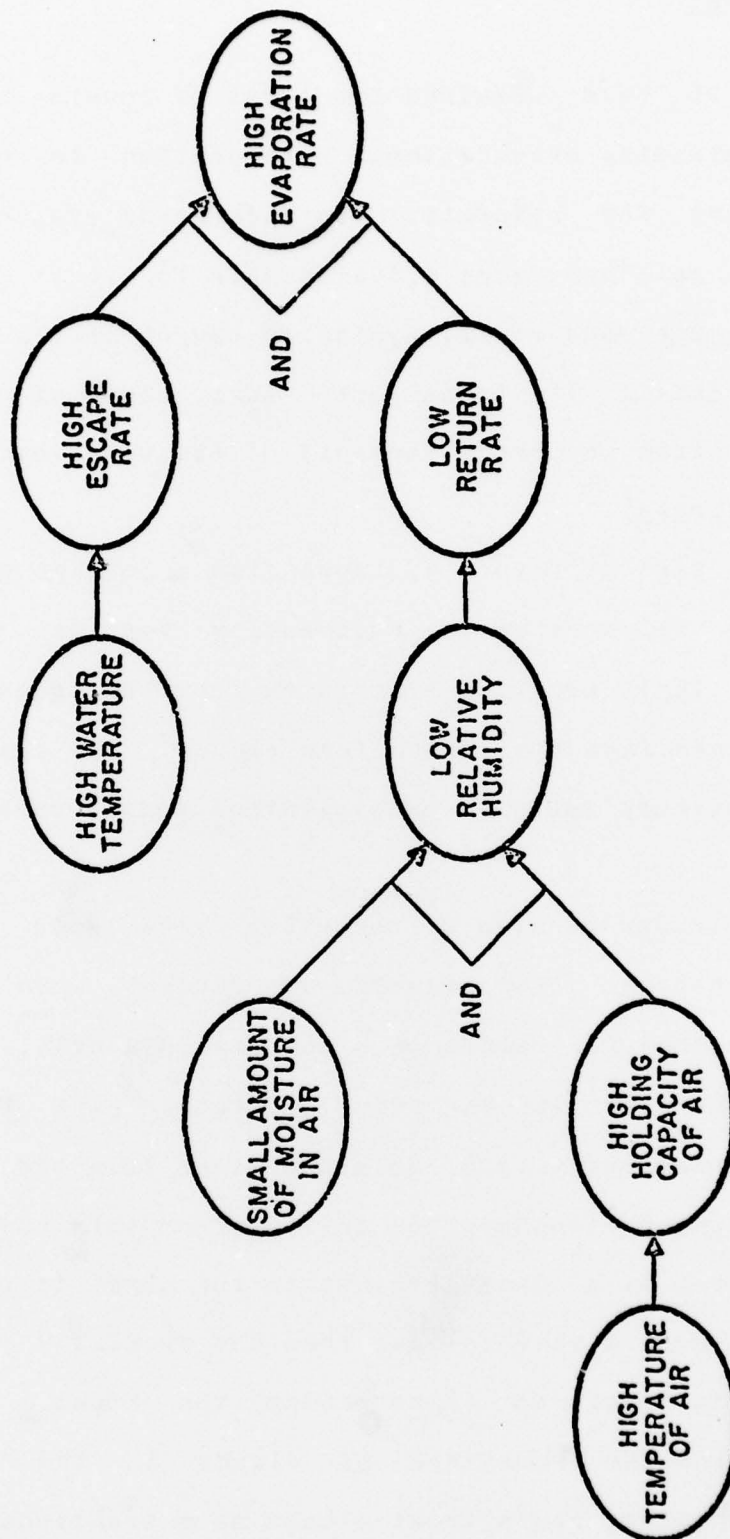
Figure 2. An and/or graph derived from the more sophisticated version of the functional model of evaporation.
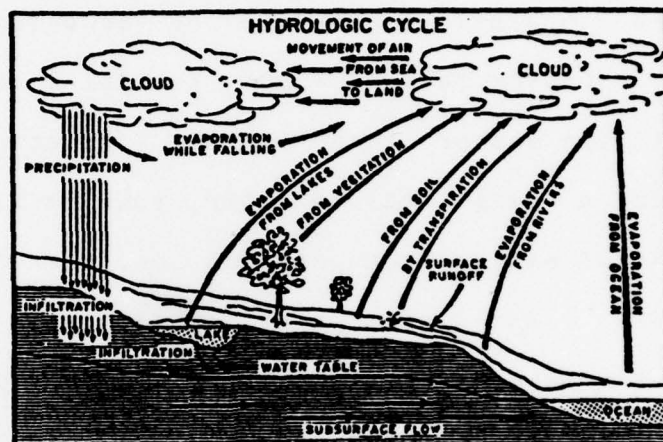
The Water-Cycle Model

So far we have examined two types of models useful for teaching and understanding evaporation. Evaporation is only one subprocess necessary for rainfall. To understand evaporation in context, there must be other, more global models to tie it in with other processes. One such model, typically taught in high school, is the water-cycle model. It turns out, that many of people's misconceptions come from incorrect variants of the water-cycle model (Stevens et al, in press).

The top part of Figure 3, taken from a college geography text, (Hoyt 1973) illustrates a rudimentary version of the water-cycle model. In it moisture evaporates from the ocean, lakes, trees, soil, etc and into the air to form clouds. The clouds move inland where the moisture falls as precipitation and is carried back to the ocean.

This particular version of the water cycle leads to many students' misconceptions. For example, one student, when asked to name the moisture source for rainfall in the Amazon Jungle, answered that it came from the river and the trees. This in part is true, but, in fact, the great quantity of moisture comes from the Atlantic Ocean. Another common misconception arising from this rudimentary model is to think that if a place is close to the ocean it will have a lot of rainfall. Such a view follows from the proximity of water and land shown in pictures illustrating the model. Another misconception concerns the importance of clouds in the rainfall process. Most meteorology texts treat clouds as a transient step in

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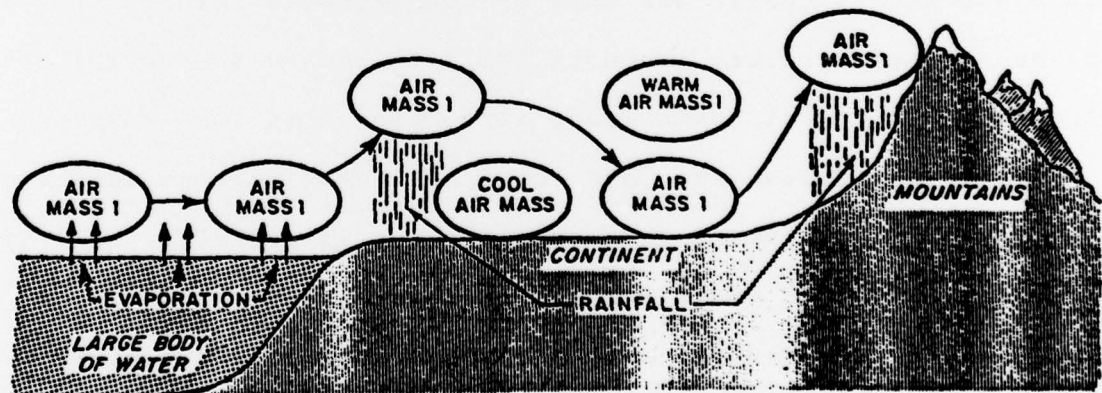

MORE SOPHISTICATED VERSION

Figure 3. Two versions of a macroscopic meteorological
model of rainfall.

the condensation process. Novices, however, tend to think of clouds as critical entities in the water cycle. This may follow largely from everyday experience of clouds, but it also relates to the model presented in Figure 3, where clouds are treated as the form moisture takes on in the air. These examples illustrate some of the dangers of teaching over-simplified models.

A more sophisticated version of the water-cycle model is illustrated in the bottom half of Figure 3. In it air masses become the critical entities rather than clouds. Moisture is seen as evaporating from a large body of water, such as an ocean or large lake. The amount of evaporation depends on air temperature and water temperature. As winds carry the air mass over the body of water, it absorbs more moisture the further it travels. When the air mass moves over land, it can encounter different obstacles. If it encounters a warmer air mass, it tends to go under that air mass. If it encounters a cooler air mass or mountains, it tends to rise. When an air mass rises, it cools rapidly leading to precipitation. As the air mass travels over land, it continues to lose moisture as it rises over obstacles, and thus has less and less moisture to precipitate. The moisture that precipitates is carried by rivers back to the bodies of water from which it evaporated.

This particular model enables people to understand many different aspects of the patterns of rainfall in the world. For example, it explains why cold fronts usually bring dry weather, why warm fronts bring rain, why precipitation frequently occurs when two air masses encounter each other, why it tends to be drier further

inland, why mountains have more rainfall than surrounding regions, etc. Together with knowledge about geography, this model enables students to make predictions about rainfall patterns in different places. As with the simulation model of evaporation described earlier, the details of a concrete water-cycle simulation are not obvious. The complete model must embody the laws, control structure and processes in a manner that makes it possible to derive relevant consequences.

As we pointed out earlier, one of the motivations for the notion of models is that students' misconceptions at our level of analysis seem to form patterns. One of the most interesting set of misconceptions seems to result from a perturbation of the water-cycle model. We call this perturbation the sponge model of evaporation and condensation. In it an air mass is viewed as expanding as it absorbs moisture out of the body of water. Then when it comes in contact with other air masses or mountains, the water is squeezed out of the air mass by the pressure from the collision. The sponge model makes sense of some aspects of the process, but it leads to serious misconceptions such as ignoring the effects of temperature on condensation. One of the important design goals for an adequate teaching system is that it recognize these incorrect models from the patterns of misconceptions that students show.

Finally, we want to point out the relationship of the water-cycle model to the kind of script-structured knowledge that was used in the original Why system (Stevens & Collins 1977;

Stevens et al, in press), and is emphasized as important for understanding everyday phenomena, such as going to a restaurant (Schank & Abelson, 1975), a birthday party (Minsky, 1975), or going to a grocery store (Charniak, 1975). A script represents certain of the critical events that occur in any process. For the water cycle, a script might include the moisture evaporating from the water into the air, being carried over the land, rising, cooling, condensing and finally precipitating. A script then consists of a set of snapshots taken at different times during the process. Where the process can take different paths depending on events in the world (such as what the opponent does in the Civil War Game), then a script has to break apart into a lattice or tree structure. But scripts inevitably sacrifice much of the inherent power in a simulation model. When people talk about their models, they inevitably describe the critical events that occur in them. Hence, they seem to be talking about scripts they have in their heads. But we would argue that in fact they may be merely describing critical events, for example, events associated with a changes of state that occur when they run their model.

A Model of Climates

The final model we want to describe involves the way water and air currents travel around the world, and what happens when they encounter different land masses. This model parallels the water-cycle model above, but it presents the events from a geographical perspective rather than a meteorological perspective.

Figure 4 illustrates a rudimentary version of this model. In it the Gulf Stream is depicted as following the coast of North America and then crossing the Atlantic toward England and Europe. As the current encounters land, it turns south along the continental border with parts going north of the continent and into the North Sea. The winds carry the moisture-laden air inland over Europe. This rudimentary model is essentially correct, but it contains very little predictive power.

A more sophisticated version is shown in the bottom half of Figure 4. This is the model that is taught in college geography texts (James, 1966; Hoyt, 1973). In it the pattern of ocean and air currents as they encounter a hypothetical continent are shown. Driven by the Coriolis effect from the earth's rotation, currents travel westward along the equator. Ocean currents turn poleward at the eastern edge of any continent and eventually form the prevailing westerlies that occur at approximately 50 to 60 degrees latitude. The circuit is completed by currents running toward the equator along the western edge of a continent. Heavy rain occurs where the ocean currents encounter land. Dry lands occur along the western edge of continents where there is a cold current offshore. The model can be much more complicated than this, involving the movement of high pressure and low pressure centers seasonally, but this gives the basic geographical model.

This basic geographical model can be derived from generalization of specific cases, such as the Gulf-Stream model. With the generalization comes genuine predictive power. One can,

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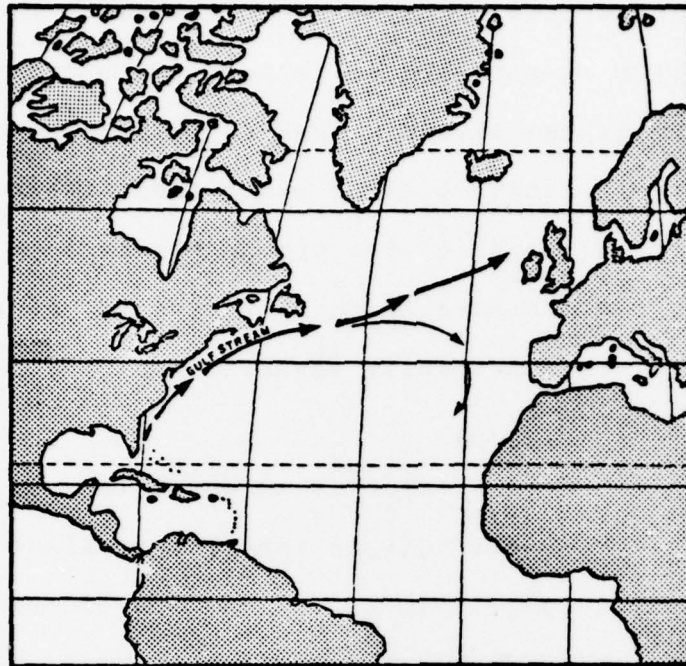
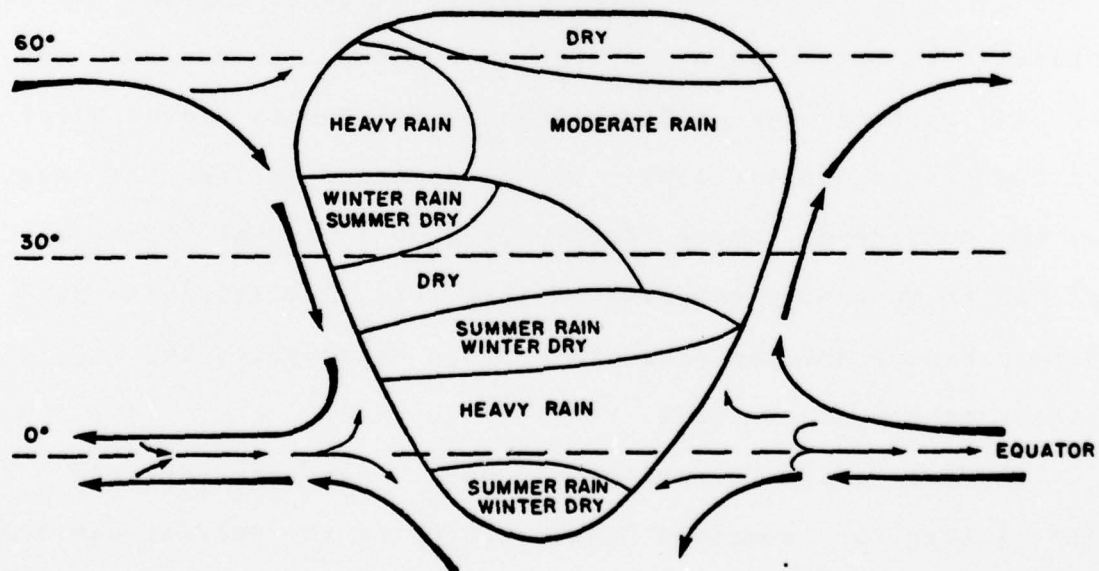

MORE SOPHISTICATED VERSION

Figure 4. Two versions of a macroscopic geographical
model of rainfall.

for example, consider the effects of putting down continents of different sizes and shapes at different places in the South Pacific. The effects on Australia are minimal, but the effects on South America can be much greater by affecting the landfall of the prevailing westerlies. Given knowledge about mountain ranges, it is possible to make quite accurate predictions about the rainfall patterns in the proposed South Pacific continent.

CONCLUSION

At one level this discussion of models is obvious. Any scientist will agree that he views the world from different perspectives, that he alternates between perspectives depending on which view is appropriate for the problem at hand, that he often checks a conclusion derived from one model by testing it against another model, etc. So this paper really is arguing for a position quite close to the common sense view that scientists already have about their own knowledge.

At another level, however, the proposal that knowledge about complex systems must be represented in multiple models has radical implications both for representing knowledge in intelligent CAI systems and for education generally. We will briefly indicate a few of those implications.

The major implications for intelligent CAI systems is that it is not sufficient to build the system based on a single perspective of the domain, nor to exclusively use static representations such as and/or graphs or scripts. Our proposal is that expert systems need multiple models that can be used generatively to test out novel hypotheses and make predictions about new situations. Furthermore they must have specific strategies that determine when to invoke one model and when another and how to map back and forth between models. In sum, representation of expert knowledge must be further removed from the surface forms in which people talk than most current systems contemplate. Unfortunately,

this makes many aspects of building expert systems more difficult.

The implications for education are equally profound. This view suggests that multiple models should be taught explicitly as alternative points of view about a topic. The emphasis should be on the kinds of situations and problems for which each model is applicable, and how to apply them to solve different types of novel problems. At the same time students should learn the limitations of each model and how to test out a solution derived from one model against another model.   Students might also be taught how various distortions of a model lead to different misconceptions and how any model can be systematically refined to increase its predictive accuracy.

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